National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Technology Development for a Stirling Radioisotope Power System

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Outline

- **Background**
- **NASA Glenn Technology Development Project**
- **Synchronized Operation of Opposed Stirling Convertors**
- **Adaptive Vibration Reduction System**
- **Summary**

Stirling Radioisotope Power System

- **High-efficiency power source to provide spacecraft on-board electric power for NASA deep space missions**

- **> 20% efficiency reduces isotope inventory by factor of 3 or more compared to RTGs**

    Reduces cost, mass, and radiological hazard

- **Joint DOE and NASA GRC project**

    Stirling Technology Company (STC) - developing Stirling convertor

- **Other Stirling space applications:**

    - Venus power and cooling
    - Lunar/Mars bases - power and cryogenic cooling
    - Planetary rovers and weather stations
    - Solar dynamic power
    - Cryocoolers for sensors

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Department of Energy

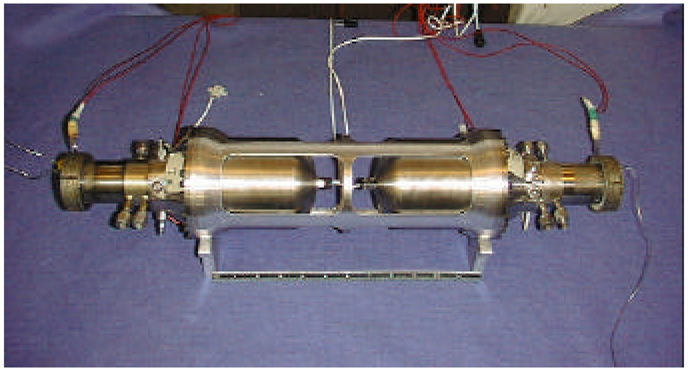
Stirling Technology Company

DOE/STC Stirling Technology Demonstrator Convertor (TDC)

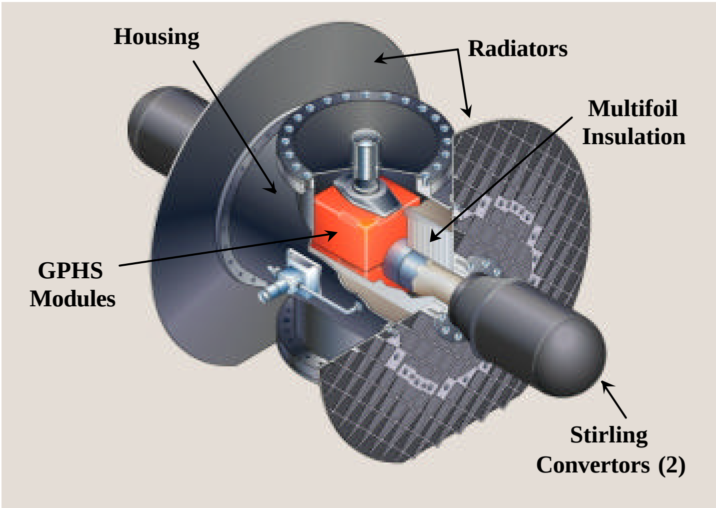
- **DOE/STC developing 55-We convertor for Stirling radioisotope power system**
  - NASA Glenn provides technical consulting under IAA

- **Four TDC convertors built to date for DOE**

Demonstrated design power and efficiency at 650 C / 120 C design conditions



Two opposed 55-We TDC convertors on test



**System concept
(courtesy of DOE)**

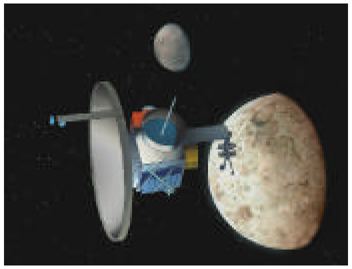
- **DOE system studies being performed by Orbital Sciences and Lockheed Martin**
  - Both two and four convertor systems under study
  - Evaluating fault tolerance

NASA Glenn Supporting Technology Project

- **Supports overall development of Stirling radioisotope power system for deep space missions**

  Builds on NASA GRC expertise developed as part of previous Stirling research, especially 25 years on free-piston Stirling

  - Radioisotope space power (free piston)
  - SP-100 space power (free piston)
  - Conservation & Renewable Energy (free piston)
  - Solar terrestrial power (free-piston)
  - Automotive (kinematic)



Deep space power

- **Provides NASA GRC tasks to develop convertor for readiness for space qualification and mission implementation (TRL 6)**

  - DOE/STC to incorporate technologies into flight prototype convertor

- **Tasks:**

  - Convertor performance verification
  - Controls technology development
  - Heater head life assessment
    Materials/joining evaluation
  - Magnet aging characteristics
    Linear alternator FEA
  - Convertor operation in dynamic launch environments
  - Convertor EMI/EMC characterization
  - Evaluate radiation survivability
  - FMECA and life/reliability assessment
  - Radiator conceptual design

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Heater Head Life Assessment

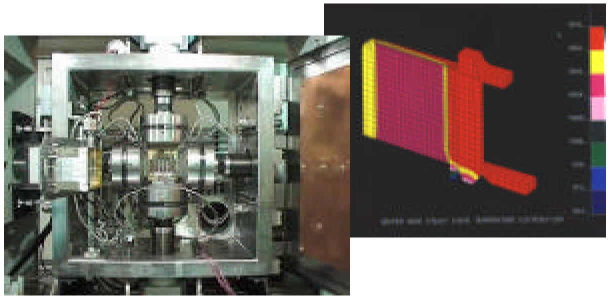
Objective: Provide confidence in achieving 100,000+ hours mission design life

- **Characterization of IN718 in final process condition**
  - LCF, creep, thermal, and tensile properties

- **Identify and develop life prediction model**

  Characterize model with IN718 data

  Conduct independent FEA of heater head



Heater head life assessment

- **Structural benchmark testing**

  Accelerated life tests on prototypical heater heads - compare to life predictions

  Re-calibrate and verify model

- **Joining evaluation**

  Thermally age and investigate microstructure of critical joints

Review organic materials - compatibility & outgassing

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Heater Head Life Assessment - Results to Date

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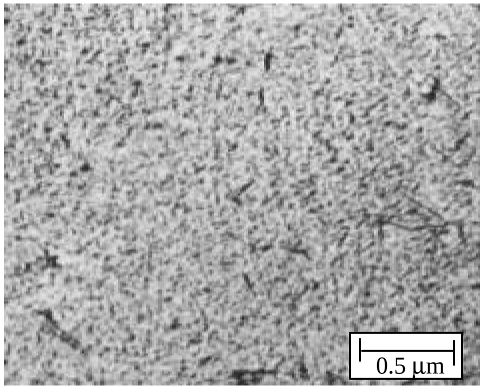
Approach: Characterize Long-Term Durability using Short-Term Extrapolation Methods

- **Characterization of IN 718 in final process condition**
  - Optimum heat treatment identified
  - Creep testing initiated with over 2000 hours of testing completed
  - Cr-loss during service determined to be negligible



Optimized IN 718 Microstructure

- **Identify and develop life prediction model**
  - Identified extrapolation models to utilize short term creep data (<20,000 hour) to predict long-term durability (>100,000 hours)
  - Generated Finite Element Analysis model of heater head design

- **Structural benchmark testing**
  - Designed & developed high temperature, high pressure test system for heater head sub-components
  - Designed hermetic seal test system to evaluate long-term joint integrity

- **Joining evaluation**
  - Preliminary assessment of joining methods for IN 718 and 304 SS complete

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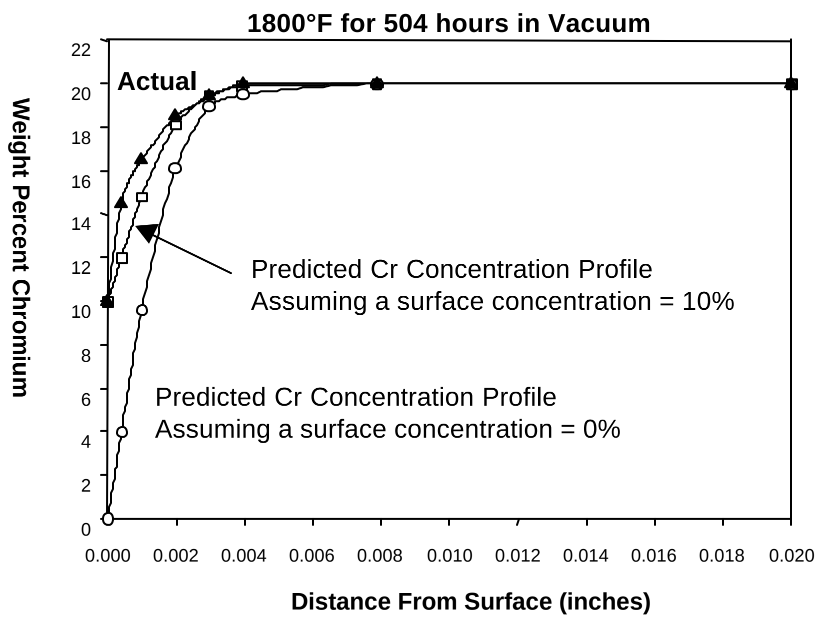
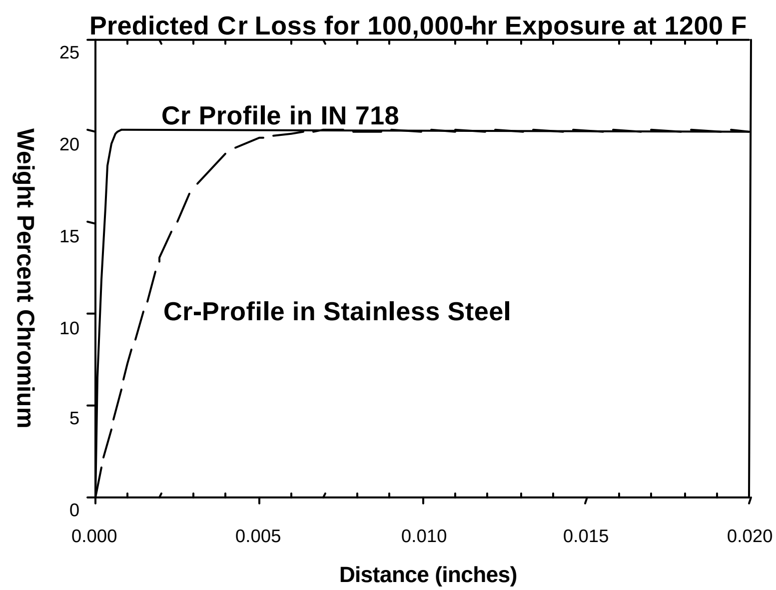
Model Predicts No Problem with Chromium Loss in IN 718 Heater Head Material

- Long-term high-temperature exposure in the vacuum of space will deplete chromium in IN 718
- Chromium depletion would decrease creep resistance and strength
- A model was characterized and verified by accelerated aging tests on IN 718



Model Verification of
Cr loss at 1500°F after 500 hrs



100,000 Hour Model Prediction:
Negligible Cr loss in IN 718 at 1200°F

Permanent Magnet Aging Tests

- **Objective: Experimentally determine long-term degradation of candidate linear alternator permanent magnets**
  - Combined effects of temperature and DC demagnetizing field

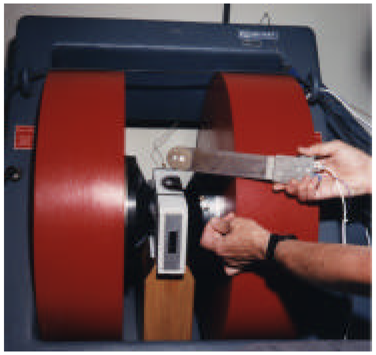
- **Magnet screening -** 3 manufacturers, 8 magnet types

  Test & characterize demagnetization resistance of NdFeB magnets as function of temperature (20-150ºC)

  Short-term (1 week) aging tests

- **Perform long-term (>12,000 hrs.) temperature aging tests at 120ºC with applied DC demagnetizing field on two selected magnet types**

- **Status: Magnet samples received**
  Characterization tests underway
  Long-term aging rig being fabricated



Magnet Test Rig

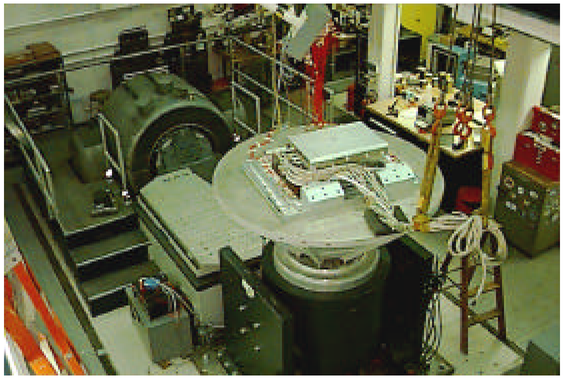
Stirling Convertor Operation in Dynamic Launch Environments

- **TDC was tested at Workmanship, JPL Flight Acceptance, and JPL Qualification random vibration levels - simulated expected launch environment**

  - NASA GRC Structural Dynamics Lab

  - Qualification test: 12.3 Grms (20-2000 Hz)
    0.2 g^2/Hz (50-250 Hz)
    3 minutes / axis

Tested with axial & lateral vibrations with TDC operating at full stroke and full power conditions



Structural Dynamics Lab

- **TDC exposed to significantly greater vibration levels than qualification levels used for Galileo, Ulysses, and Cassini RTGs**

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Stirling Convertor Operation in Dynamic Launch Environments

Power & On-Board Propulsion Technology Division

Results

- **TDC successfully passed testing with no structural or functional performance problems**

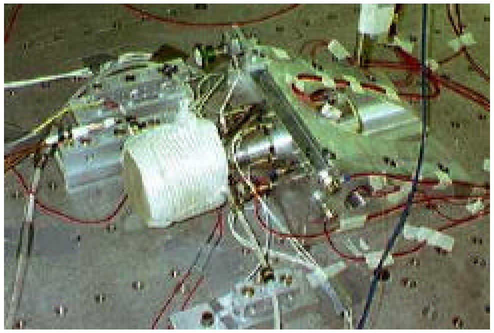
  Convertor power and efficiency were same before and after each test

- **Full power output (54-55 We) on average throughout axial tests - with instantaneous surges and dips**

  Power output degraded during lateral tests with a minimum of 38 We

- **TDC structure is dynamically well-behaved with no dynamic coupling problems**

  - Low-level sine sweeps used to compare dynamic signatures

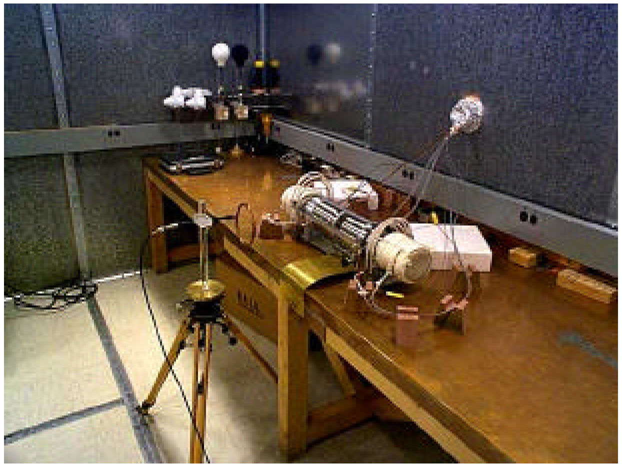


TDC on test in the Structural Dynamics Lab

- **Disassembly and inspection at STC showed no major areas of concern attributable to vibration test**

Stirling Convertor
EMI/EMC Characterization

- **TDC magnetic and electrical fields characterized in NASA GRC EMI lab**
  - NASA GRC, JPL, Lockheed Martin
- **Meets all EMC requirements for Europa Orbiter and Pluto Kuiper Express missions**
- **Solar Probe has extremely tight H-field and low frequency E-field requirements**



TDC on test in EMI lab

TDC not designed to minimize loop areas or provide magnetic shielding - some modifications needed:

- Significant improvement likely by laying out wiring to minimize current loops or control via counter loops
- Additional magnetic shielding will probably be required
- Use proper cable terminations and shielding on linear alternators

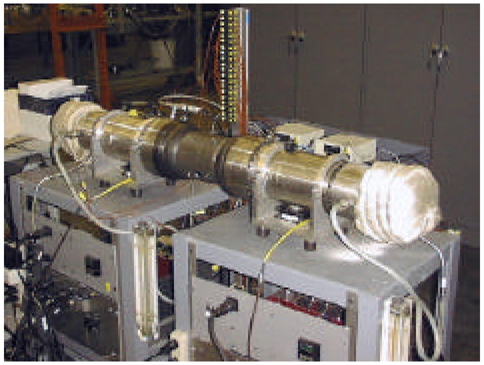
Other Tasks

- **Candidate organic replacement materials for the TDC linear alternator have been identified as necessary for use in high Europa radiation environment**

  - Consulted with JPL, GE, NASA GRC, and Lockheed Martin experts

  - 10 MRad environment with 50-mil Al shielding
    4 MRad with 100-mil Al shielding

  - Now evaluating piston bearing coatings and bumpers, alternator adhesives and electrical insulations



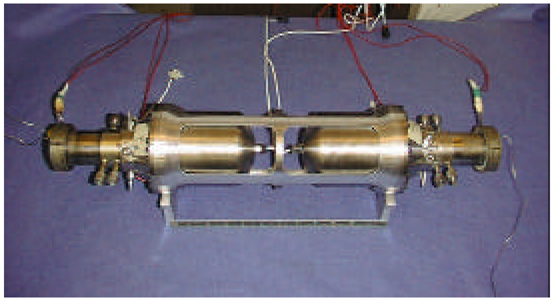
350-We convertors

- **Initial FMECA and life & reliability assessment completed**

- **Now establishing Stirling convertor test cells**

  - Two 350-We convertors on test - spring 2000

  - Two 55-We convertors on test - summer 2000



55-We convertors

Performance verification and controls technology development

Synchronized Stirling Convertors

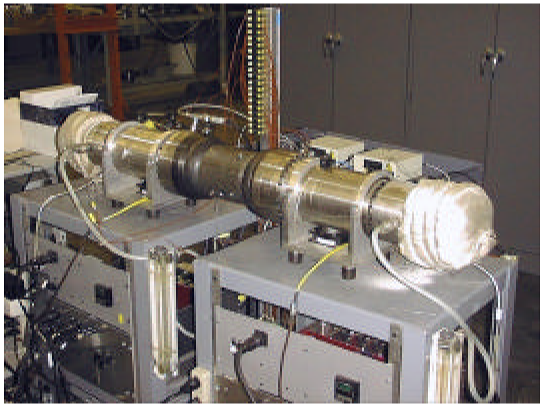
STC Phase II SBIR

- **Successfully demonstrated synchronous operation of two opposed 350-We thermodynamically-independent Stirling convertors**

  Multiple convertors are critical for reliability and modularity

  Connection now being used for DOE/STC 55-We TDC convertors

- **Parallel AC and mechanical connections**



Two 350-We RG-350 synchronized convertors

- **Achieved synchronization over wide range of operating conditions, including simulated degradation**

  40-50 x vibration reduction relative to unbalanced convertor - well below pixel smear limits for deep space sensing

- **Initial development of artificial neural network to monitor convertor health using only non-invasive instrumentation**

Synchronization with Simulated Degradation

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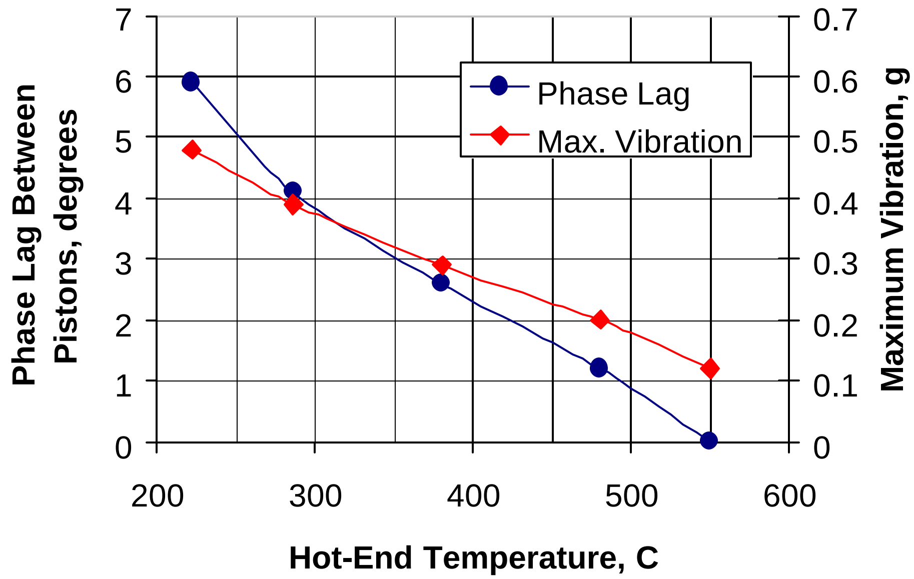
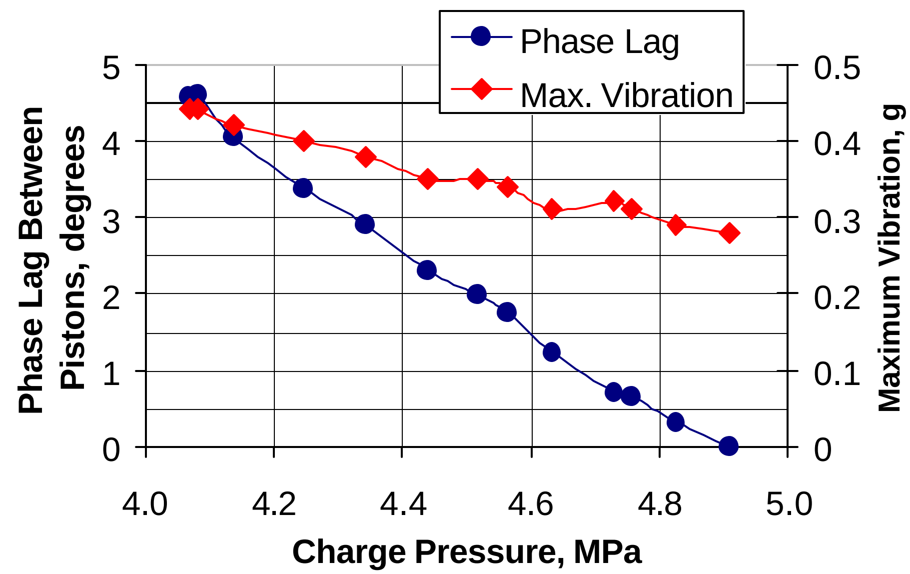


- **Synchronization shown to be very robust**
  - Simulated degradation
  - Transient testing

- **Varied hot-end temperature and charge pressure in one convertor over wide range**
  - **Maintained synchronization**
  - **Only slight increases in vibration**



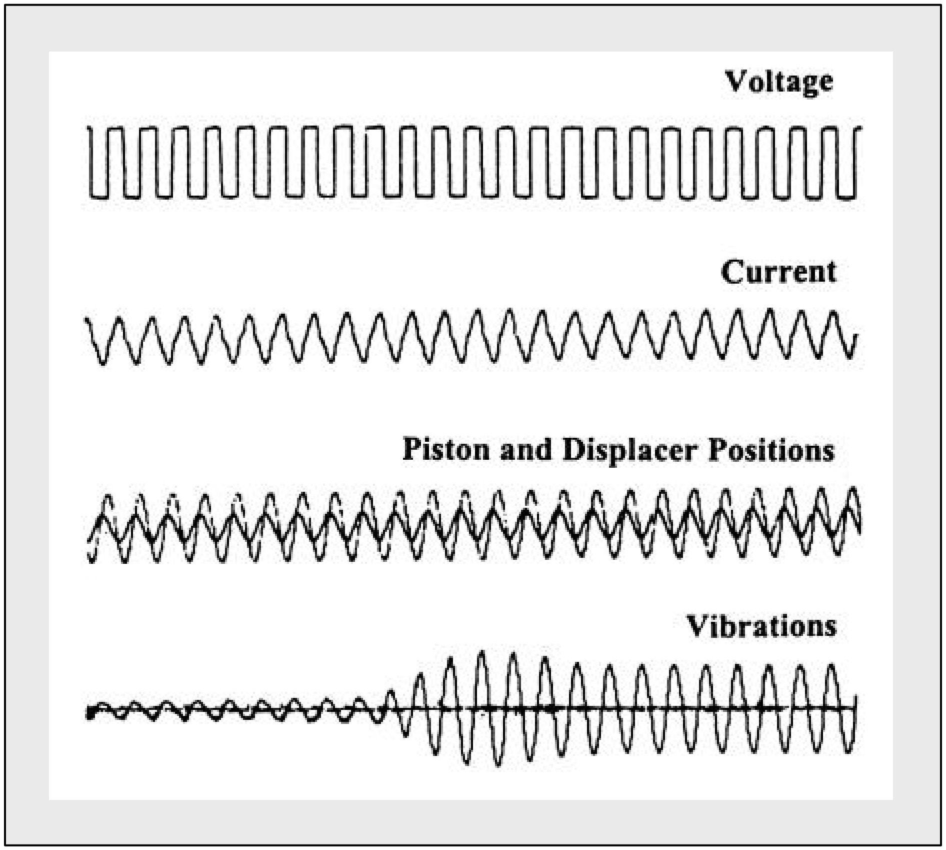
Transient Test Results

- **Various connections/disconnections showed ability to achieve synchronization rapidly and reliably**

- **No large transient overstrokes or any other potentially damaging results**

  - Only expected vibration increase when disconnect

  - Acceleration spike to 6-10 g's when connect - settles out quickly and can be mitigated if necessary



Response when parallel electrical connection is broken and one convertor is shut down

Adaptive Vibration Reduction System (AVRS)

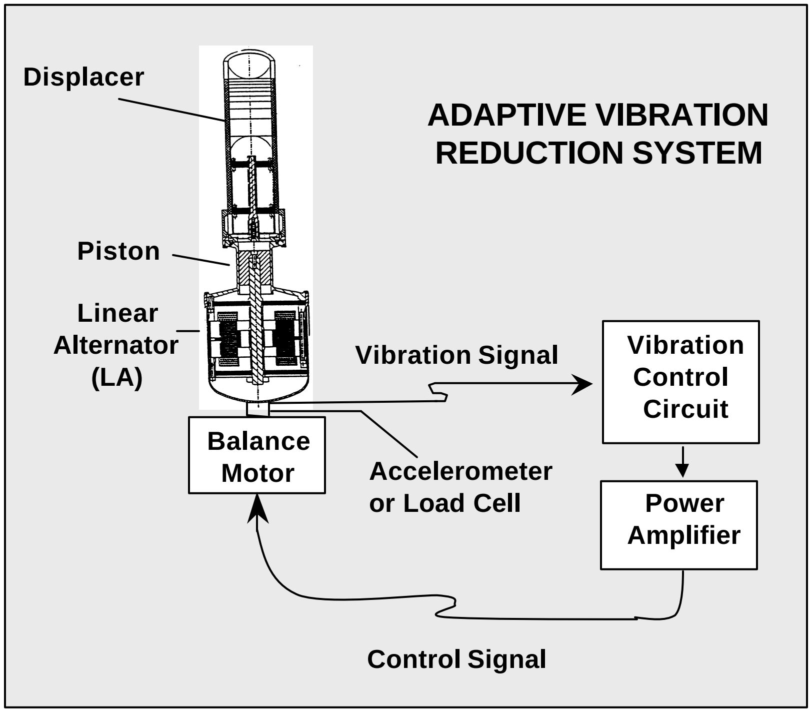
STC Phase II SBIR

- **Key Stirling need is to eliminate vibrations over 10-15 yr. mission life**

- **AVRS will further decrease vibrations under normal operating conditions**

  And, even more importantly, adapt to changing convertor conditions and any degradation or failure

- **Goal is 100 x total reduction in unbalanced vibrations under all conditions**
  - Balance fundamental and up to 10 harmonics



- **STC has demonstrated 0.007 g vibration on cryocoolers with similar techniques**
  - Varying frequency is key difference for power convertors

Adaptive Vibration Reduction System (AVRS)

Initial Results

- **Initial tests of AVRS on 350-We convertor have shown:**

  500 x total vibration reduction under normal conditions with only 2 W of power dissipation

  50 x vibration reduction with simulated failed convertor and only 7 W of power dissipation

- **These tests only balanced fundamental and used simple algorithm**

- **Final demonstration of AVRS will be on 55-We TDC convertors**

AVRS balance motor

(need 1 motor per 2 convertors)

Summary

- **NASA GRC, DOE, and STC are developing Stirling convertor for radioisotope power system to provide on-board power for NASA deep space missions**

  - Replace RTGs with high-efficiency power source

- **NASA GRC is conducting an in-house technology project to assist in developing convertor for readiness for space qualification and mission implementation**

  - Stirling convertor successfully passed launch environment random vibration testing at qualification levels while operating at full stroke and full power

  - EMI/EMC characterization showed convertor meets requirements for Europa Orbiter and Pluto Kuiper Express - needs some modifications for Solar Probe

  - Heater head life assessment and magnet aging characterization tasks underway

  - Substitute organic materials identified for use in Europa high radiation environment

- **Developing key convertor technologies under NASA SBIRs with STC**

  - Demonstrated 500-fold reduction in vibration levels - well below pixel smear limits